Numerical Assessment of an Imperfect Pile Group with Defective Pile both at Initial and Reinforced Conditions

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Abstract. The assessment of problems of imperfect, damaged, pile groups is scarce in the geotechnical literature. Besides, techniques of assessing the performance of the foundation system once a defect is found are seldom presented, as well as real examples of the behavior of large scale imperfect foundations after their remediation. Therefore, this paper has extended the design philosophy of "piled raft" foundations to predict the numerical behavior of imperfect pile group foundations at pre and post-remediated conditions. Focus will be given to the problem of groups with either defective shorter length or lower stiffness piles, caused by natural or man-made sources. The remediation of the group is considered via added reinforcement piles with either similar or dissimilar characteristics (length, diameter, stiffness) compared to the original undamaged piles. Although the results are limited, they allow preliminary generalizations of the overall group behavior at working conditions, once a pile flaw is noticed and after the remediation has taken place. Among other results the paper highlights the load sharing mechanism between foundation elements, which relates to the position and magnitude of damage of the defective pile, as well as to the overall characteristics of reinforcement one. It was concluded that a defect caused by an unwanted pile length variation can be more detrimental to the foundation system than an unexpected low structural stiffness for the constructed pile. The derived factor of safety (SF) of the system (overall value) and of its distinct components (individual values) are also influenced by aforementioned variables, leading to questions on how the reinforcement can be made in such manner to obtain well optimized SFs. As noticed throughout the analyses, defective piles share its load with system components, once a defect appears. Nevertheless, even when imperfect such piles continue to absorb some load, although to a lesser degree than the original value. The reinforcement piles tend to absorb (or retain) some of the load spread by the defective ones, in a proportion which depends to its general characteristics (size, position, stiffness). Again, questions about an optimization procedure have to be made in order to wisely and economically use this particular observed feature on the remediation design.

Keywords: defective pile, imperfect pile group, remediation, numerical analysis, piled raft.

1. Introduction

The design of deep foundations underneath high-rise buildings or bridges almost invariably assumes that most, if not all, of the piles are of the same characteristics (length, diameter, stiffness) and constructed without structural or geotechnical imperfections (defects).

Such hypotheses may be valid for many constructions, although quality control of the executed pile is rarely undertaken on conventional works, with exception of some special pile types, as continuous flight augers with their instrumented insertion procedures. Therefore, it may be possible to find, in many pile groups, piles of different lengths or even piles with defects arising from careless construction techniques.

Once the defect, or imperfection of the pile, is found, it is necessary to assess the possible performance of the overall foundation system, to see if it will continue (or not) to be favorable in regard to initial design considerations. Otherwise, some sort of remedial action may be required, such as the insertion of reinforcement piles combined with a geometrical change of the top raft (cap) of the imperfect pile group. Of course geometrical changes of the group would be feasible only if the imperfection could be found out at early stages of the construction, when the loading of the foundation is not at its upmost value.

Given the fact that, according to Janda *et al.* (2009), the term "piled raft" is generally expressed (and was defined in this publication) as a "foundation system in which both structural components (piles and top raft) interact with each other and with the surrounding soil to sustain vertical, horizontal or moment loads coming from supported superstructures", one should realize that any imperfect foundation group with defective(s) pile(s) will behave as a "piled raft". That means, the system will share load in between its elements (raft, piles, surrounding soil) due to an uneven performance of the good quality and the defective pile(s) in the same foundation system. In other words, interaction between dissimilar piles and the raft will unavoidably take place. Therefore, the analysis of pile groups with defective pile(s) is a special analysis of a piled raft system, in which one or more piles have special distinct characteristics, such as length, diameter or stiffness.

Similarly, the remediation of the imperfect group by the insertion of similar or dissimilar piles can also be a

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problem related to the behavior of a piled raft system, especially if it can be assumed that the reinforcement piles (and geometry change) are considered in the beginning of the loading process, thus compatible with the fact that the imperfection was detected at an early work stage.

The motivation of this particular (piled raft) analyses and discussion comes from the fact that the assessment of problems of imperfect pile groups is scarce in specialized publications and, not rarely, is hidden to practitioners/researchers under confidentiality or commercial non publication clauses. Few publications deal with this topic, particularly related to site behavior of pile groups with defective pile(s) of distinct categories (shorter length, lower stiffness, structural damages, and so on), and their performance once some sort of remediation is put in place. Also, techniques of assessing the performance of the foundation system, either analytically or numerically, are seldom presented in technical literature, as well as successful examples of large scale reinforced foundations.

In this regard, and from the publications available to the authors, one may refer to Lizzi (1982), Sales & Costa (1996), Poulos (1997, 1999, 2005 and 2009), Gotlieb & Gusmão Filho (1999), Ferreira *et al.* (2000), Lima & Costa Filho (2000), Knigmuller & Kirsch (2004), Milititsky *et al.* (2005), Ziccareli & Valori (2006) and Cordeiro *et al.* (2008a, b) to read more about imperfect pile groups and possible reinforcement systems. Note that, with exception of some of Poulos papers, none of them present in a clear manner the analytical approach used for the insertion of additional piles, *i.e.*, how calculations and decisions were made as well as field performance of the reinforced group(s).

This paper will therefore focus on the problem of defective pile groups with either (a) shorter length or (b) lower stiffness piles, caused by natural or man-made imperfections. It will detail the conventional numerical methodology to forecast the behavior of traditional piled raft groups, and how this methodology can be used to perform parametric analyses of hypothetical post-reinforced cases. That means, pile groups in which the remediation was carried out at early stages of construction work, hence where it was possible to implement a geometrical increment of the top raft combined with the insertion of a reinforcement pile to substitute the defective one. It needed to be considered as an "insertion" at initial stages of loading due to limitations of the adopted numerical tool.

The reinforcement pile was considered either with similar or dissimilar characteristics (length, diameter, stiffness) as the original undamaged piles of the group.

The paper will present all the parametric analyses for a particular case in study derived by a M.Sc. recently defended in this area (Cordeiro, 2007). Although a unique example is shown, due to paper size limitations, the discussion and conclusions apply for other hypothetical cases of similar characteristics.

2. Concepts On Imperfect Pile Groups

According to Poulos (2005) in his state of the art (40^{th} Terzaghi Lecture) the imperfections that may have impact on pile foundation performance may arise from a number of sources, including natural and construction aspects, inadequate ground investigation, pile load testing, and loading during operation.

In terms of natural sources, the dissimilar piles arise from the existence of layers that are not horizontal or continuous, or from undetected boulders within a soil layer, from sloping bedrock, intrusions of rock over limited areas of the site, from cavities in limestone rock, or simply by the presence of softer layers below what might be regarded as suitable founding strata for the piles. These aspects are shown in Fig. 1.

On the other hand, construction related imperfections arise from processes inherently linked to execution aspects of the piles, *i.e.*, either from inadequate field quality control or from inevitable consequences of construction (man made) activities, as for instance: (a) soft base on bored piles due to inadequate base cleaning; (b) necking or other defects within the shaft of piles; (c) inadequate forecast of the real founding conditions; (d) lack of proper base inspection in manually excavated foundations; (d) ground movements developed due to drilling, or construction activities (dewatering, excavations, surficial loading) during pile execution; (e) careless use of some intrinsically related technologies to particular piles, as excessive driving, poor quality bentonite mud, etc.

So, according to Poulos (2005) the construction-related imperfections in piles can be broadly classified into

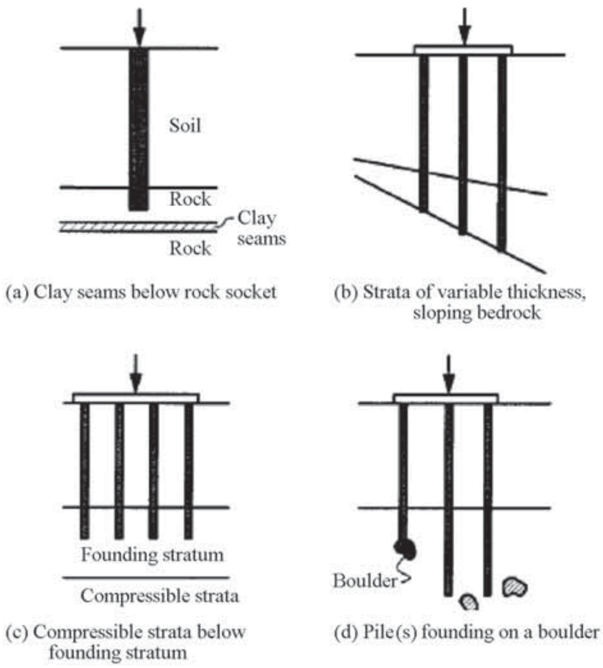

Figure 1 - Examples of imperfections by natural sources (after Poulos, 2005).

two main categories, which are related either to structural defects or to geotechnical ones. For instance, structural defects can result in dissimilar size, strength, and/or stiffness for some piles, being therefore of distinctive characteristics compared to others in the same group, or as initially assumed in design. Geotechnical defects usually arise from either a poor assessment of the in situ conditions during design and construction, or else from construction related problems, and may result in dissimilar piles with distinctive (reduced) shaft friction and end bearing resistance from others of the same group, or with different operational conditions as initially forecasted by designers. These aspects are visualized in Fig. 2.

Hence, according to Poulos (2005) the imperfections that have impact on pile foundation performance may arise from a number of sources, including natural sources, inadequate ground investigation, construction, pile load testing, and loading during operation.

Based on a history of problems noticed by the authors in foundation sites for conventional residential and commercial buildings within the respective areas of their (academic and technical) interactions, it can be said that most of the detected problems are indistinctively related to both natural and construction sources. In fact, many of the problems appear to be related to shorter than designed piles, due to natural sources (boulders, hard strata), man-made construction mistakes, or structural defects (as necking). In many cases where necking appears to exist (via post execution pile integrity tests), it may be possible to consider the tested pile of dissimilar characteristics in relation to others of the same group, with a shorter length valid up to the point where the potential necking is detected. Moreover, in a particular case of knowledge by some of the authors, geotechnical related problems made necessary the overall reinforcement of a building simply by the fact that the piles were not properly founded on competent strata (hence, with lower than forecasted end bearing).

Therefore, the paper will focus on piles with dissimilar characteristics which are related to either shorter length

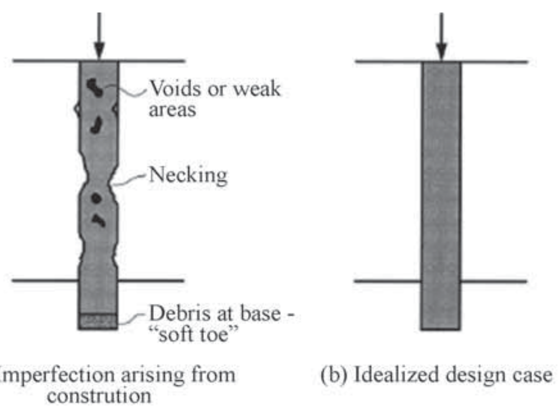

Figure 2 - Examples of imperfections by construction aspects (after Poulos, 2005).

or lower stiffness than others of the same group, as according to local experience this seems to be the major problem found on imperfect pile groups of the region. Besides, only hypothetical cases of reinforcement are presented, given the lack of good examples, or, better, unclassified examples where one could openly apply the numerical technology to be described herein.

3. Numerical Methodology

A specific numerical program was adopted in order to handle the simulations with all requirements for the analyses, in which one could take on account all (or most) of the aforementioned imperfections listed for typical defective piles. In particular, the analyses would need to handle some key aspects of the problem, as already mentioned by Poulos (2005):

• Heterogeneous or different soil profiles along the piles of the same group;

• Piles of different length or diameter within the same group, including consideration of interaction among dissimilar piles;

• Piles containing structural defects or changes in diameter or size along the length;

• Piles that would be activated part-way through the loading process to simulate the installation of reinforcement piles;

• Vertical loadings to be imposed from ground movements, as well as from normal structural loadings; and

• Piles with nonlinear shaft-soil response, and also nonlinear structural behavior.

From the available programs, the software GARP7 (*Geotechnical Analysis of Raft with Piles*; Poulos and Small 1998, modified by Sales, 2000) was adopted by Cordeiro (2007) in his Thesis to evaluate the behavior of the several imperfect pile groups with defective piles, some of them presented herein. This program is based on a simplified form of boundary element program in which the raft is represented as a linear elastic plate and the soil can be modeled either as an elastic layered continuum or as a Winkler spring medium. The piles are represented by elastic-plastic springs that can interact with each other and with the raft. Limiting values of contact pressure (beneath the raft) and pile capacity (shaft friction plus tip end bearing) can also be specified, and the raft is analyzed using the finite element technique, rather than via finite differences.

This particular software has already been used under another study (Cunha *et al.* 2001) for the analyses of standard piled raft groups, and has proved to be preferable to be used as the initial step for an academic study of this particular topic, given its high degree of approximation, simplicity and speed for usage, and facility to be adapted for carrying out parametric studies as well as solving real-world problems.

This opinion is also similar to that of Poulos (2005) in his state of art Report, who states that more complex (3D finite element – FEM) programs may take on account most, or eventually all, of the important aspects inherently related to defective pile studies, but "at the expense of a relative greater amount of time involved in setting up and modifying distinct meshes, plus the general difficulties of discerning broad patterns of behavior from the parametric studies".

On the other hand, GARP7 can effectively and quickly simulate defective pile groups with most of the aforementioned requirements, as nonlinear pile-soil response, dissimilar piles with distinctive length, diameter and stiffness in the same group, or heterogeneous soils profiles.

However, the activation of reinforcement piles at any stage of the loading process (or once the defect is more noticeable) is not possible, which has turned the analyses to be valid solely for post-reinforced systems in which the remediation was carried out at early stages of construction work and (vertical) loading. Nevertheless, an ongoing D.Sc. Thesis is presently underway to cover for reinforcement groups at distinct levels of the loading stage (using a more refined 3D FEM software – LCPC Cesar).

GARP7 considers "interaction factors" between the springs that represent the piles of similar or dissimilar characteristics. Such factors are computed via the use of another well-established software program called DEFPIG (*Deformation Analysis of Pile Groups*; Poulos, 1990). It was originally written for a group of identical elastic piles having axial and lateral stiffness that are constant with depth. However, it also allows for the eventual slippage between the piles and the surrounding soil, and it can take into account the effects of soil non-homogeneity along the length of the pile. The stress distributions are computed from the theory of elasticity, more specifically from Mindlin's solutions for an isotropic, homogeneous, linear elastic medium.

The first stage of the DEFPIG analyses is the evaluation of the interaction factors, by using a two pile (pile to pile) integration approach via Mindlins theoretical equations. GARP program then evaluates other factors (raft to raft, pile to raft) based on Boussinesqs equations and a fraction of aforementioned obtained (pile to pile) values. In sequence it constructs the matrices of interaction factors for the specified group (pile to pile, pile to raft and raft to raft) and moves towards the assessment of the computed stresses in each of the system components (pile, raft and soil elements).

GARP program uses two methodologies to determine the interaction factors, namely those from Randolph (1985) and from Poulos (1988). The main difference between them is the fact that the former adopts non homogeneity for the soil along the pile length whereas the latter employs a homogeneous soil condition throughout the length. Cordeiro (2007) has demonstrated that both methodologies yield slightly different answers in terms of non dimensional charts of the interaction factors *versus* pile spacing over diameter (S/D) of the piles when related to some of the system variables, as the relation of deformable strata over pile length (H/L). Given this particular aspect, it was suggested by Cordeiro (2007), and adopted herein, Randolph's methodology since it has proven to lead to a more uniform output of results. Nevertheless, as already pointed out elsewhere, this is an open point which still requires further validation – especially for Brazilian non classical (tropical) soil conditions.

In the present series of studies the following characteristics for the simulated groups were adopted:

• A linear elastic flexible 60 cm thick initial rectangular raft (2.3 x 3.8 m) , with 6 piles of 50 cm diameter (D) and 10 m of length (L_p) equally spaced 3D apart;

• Linear elastic piles with either similar (length, diameter and stiffness) or dissimilar characteristics;

• Linear elastic, isotropic, horizontally semi-infinite soil medium, free from adjacent loadings or interferences, with a thickness of 20 m up to the rigid base (2 times the similar pile length);

• Defects related to either distinct length or stiffness for the defective (dissimilar) pile. The variation of pile length simulates broken joints, necking or geotechnical aspects (boulders, etc.), whereas the variation of the structural stiffness denotes man-made construction problems (as pile molding, concrete quality, etc.) that could generate imperfect piles;

• Remediation related to reinforcement piles of either similar characteristics of the original pile group or dissimilar characteristics (50% of length, diameter, or stiffness of original piles). The remediation was simulated by four hypothetical scenarios, each one with a unique reinforcement pile located at an enlarged position of the original raft;

• Vertical constant load level equivalent to the work condition of the original similar pile group (4.6 MN applied at the geometrical center of the raft). This value leads to an overall geotechnical factor of safety for the group equal to 2 - level where the effect of a defective pile is simulated. The remediation is also simulated at this level, but considering that the reinforcement pile was incorporated at an early stage of pile group construction, and load was carried out up to the work level;

• Results in terms of load sharing and distribution, raft moment and displacement, pile reaction, and individual pile, and overall group, safety factor are presented for pre and post-reinforcement scenarios.

The stiffness (K = load/settlement) of each structural pile element of the foundation system was determined with the use of the program DEFPIG, assuming soil conditions and pile geometry in accordance to each analysis (to be presented next). For each particular condition that was analyzed, for instance for the cases with shorter length or variable Young modulus, this program has calculated and given distinct stiffness values K, used in following GARP analyses. Hence, by doing so, the defective pile was simulated with a different K value as those of the original intact piles, and the reinforcement pile had similar or distinct characteristics as those of the original piles, depending on the remediation conditions (similar or dissimilar piles). Constant K values were respectively adopted for undamaged and defective piles since the load-settlement curves were assumed as linear elastic.

Having said that, the adopted values are given as follows:

• K of intact pile equals to reinforcement pile ("similar" pile case) = 192678 kN/m;

• K of defective pile equals to reinforcement pile ("dissimilar" pile case) = distinct for each case of shorter length L or lower modulus E:

a. 80%L: $K_{80\%L}$ = 187969 kN/m;
b. 50%L: $K_{50\%L}$ = 153609 kN/m;
c. 30%L: $K_{30\%L}$ = 71942 kN/m;
d. 80%E: $K_{80\%E}$ = 175746 kN/m;
e. 50%E: $K_{50\%E}$ = 143266 kN/m;
f. 30%E: $K_{30\%E}$ = 113895 kN/m;

4. Parametric Analyses

Based on previous descriptions, Fig. 3 introduces a perspective, cross section and upper view of the original group of similar piles studied herein, whereas Table 1 presents some of the variables depicted in Fig. 3.

The following charts show the behavior of the raft in the AA cross section, *i.e.*, central section of the raft. The paper has adopted settlements in form of normalized displacements to a vertical constant load level, which is equivalent to the working conditions of the original similar pile group.

4.1. Initial conditions of the imperfect group

The behavior of the original (perfect) model group once an imperfection (defective pile) is imposed was studied at mid width of the raft, *i.e.*, at the (AA) cross section depicted in Fig. 3 which passes through its geometrical center. For that, a particular section of the finite element mesh was considered at this position.

Table 1 - Variables for group of similar piles.

Variable/symbol	Value
Raft length (L)	3.8 m
Raft width (B)	2.3 m
Load column side (a)	0.5 m
Pile distance (d)	1.5 m
Young modulus of raft (E_{raft})	20 GPa
Poisson of raft (ν_{raft})	0.2
Young modulus of pile (E_p)	20 GPa
Poisson of pile (ν_p)	0.2
Young modulus of soil (E_s)	50 MPa
Poisson of soil (ν_s)	0.3

Also in this same figure, it is possible to notice the denomination (numbering) of the similar piles. For the purpose of this paper, piles number 1 and 3 are those which will be simulated (non simultaneously) as defective in the following analyses.

Figure 4 (a) and (b) presents the normalized displacement behavior (ρ is the vertical settlement at each point) along the raft length for an imperfection respectively on pile 1 (P1) and pile 3 (P3). For each defective pile, a simulation was made on its length (80, 50 and 30% of the original length of the similar piles) and on its Young modulus (80, 50 and 30% of the original value of the similar piles).

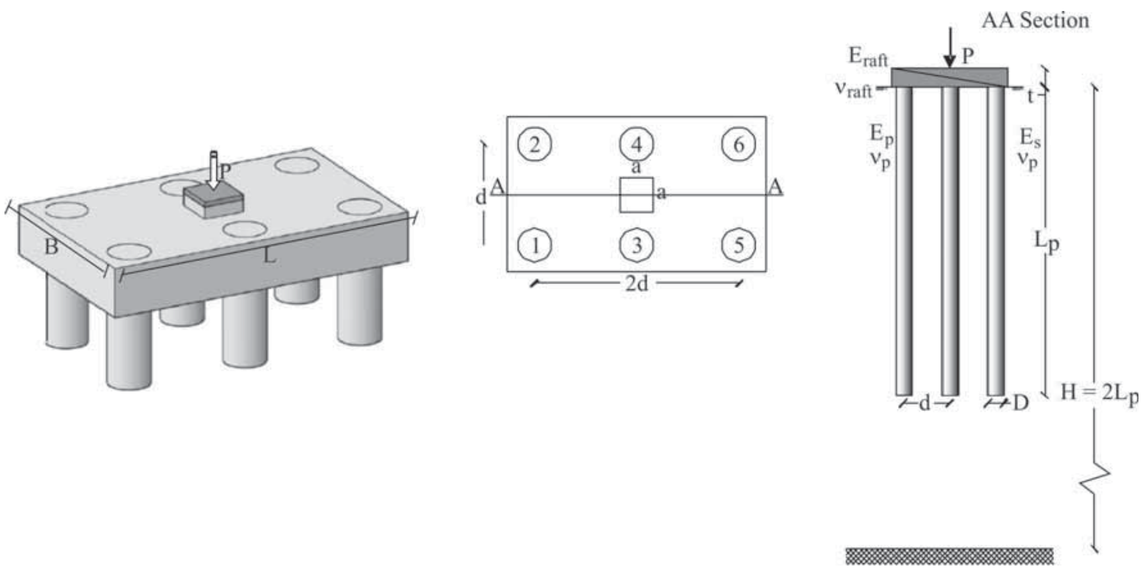

Figure 3 - General characteristics of the original group of similar piles.

Figure 5 (a) and (b) presents similar set of analyses for the raft moment generated along its length. In both cases, the “perfect group” condition refers to the original case, where the group of similar piles is loaded without any sort of imperfection.

From these initial set of results, one may notice that:

• A pile defect caused by a variation on its length is more influential on the raft settlement and moment than a proportional defect caused by a variation on the pile stiffness;

• A distinct position for the defective pile generates a slightly different pattern of observed results for both normalized settlement and moment of the imperfect pile group. It also changes the percentage difference of either normalized settlement or moment when it is generated by a length versus a stiffness defect. For instance, for a defect on pile 1, and for the highest level of defect (30%), the results in terms of normalized settlement can vary to up 25% depending on the defect type (length or stiffness). On the other hand, if the same defect is on pile 3, such maximum percentage difference drops to around 5%. The percentage difference is also variable along the raft’s length;

• For any case of imperfect pile group, the normalized settlement is more influenced by the defect than the raft moment. For instance, for a defect on the length of pile 1, and for the highest level of defect (30%), the normalized settlement can be up to 45% higher than the equivalent value for the original (perfect) group. On the other hand, on similar conditions, the maximum difference of moments drops to 10%;

• Also for any case, the imperfect pile group attains higher values of normalized settlement and moment than equivalent ones of the original perfect group. For the particular cases of P1, the imperfection not only causes a higher settlement, but also starts to tilt the raft towards the position of the defective pile.

Figure 6 and Table 2 respectively present the reactions and the safety factor (SF) for the imperfect pile group once the defect is located on pile 1, whereas Fig. 7 and Table 3 present similar results valid for a defect on pile 3. The SF is expressed in terms of (a) individual values for each of the piles, *i.e.*, the amount of individual bearing capacity divided by the load they receive at working conditions; and (b) the overall value for the whole group, *i.e.*, the amount of bearing capacity of the raft plus all piles divided by the working load.

It should be noted that such definition of overall safety factor was adopted for simplicity reasons, given the fact that a cross comparison of results was the main objective here. It is known that a more refined definition for piled rafts could be adopted (Sanctis and Mandolini, 2006).

Tables 2 and 3 are also divided, line by line, on the level (severity) of group imperfection. The first line refers to original (perfect) group conditions, where all piles are operative and similar, while the last one refers to a fully defective condition for either piles 1 or 3, *i.e.*, assuming that they simply do not exist. Imperfections related to a distinct length or stiffness for the defective dissimilar pile are also presented.

From these results, one may notice that:

• At perfect conditions the overall safety factor is 2, whereas individual factors for each pile vary from ~1.5 to 2.5. Such variation is normal, given the fact that the raft is not perfectly flexible and readjusts itself to the applied load,

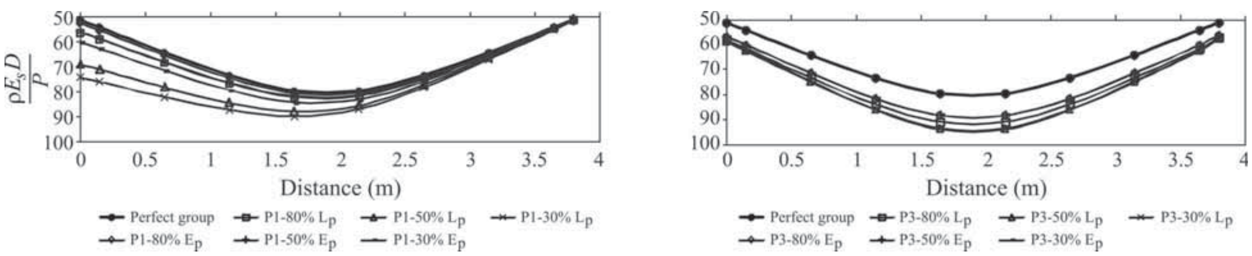

Figure 4 - Group behavior in terms of normalized vertical settlement for imperfection on (a) pile 1 and (b) pile 3.

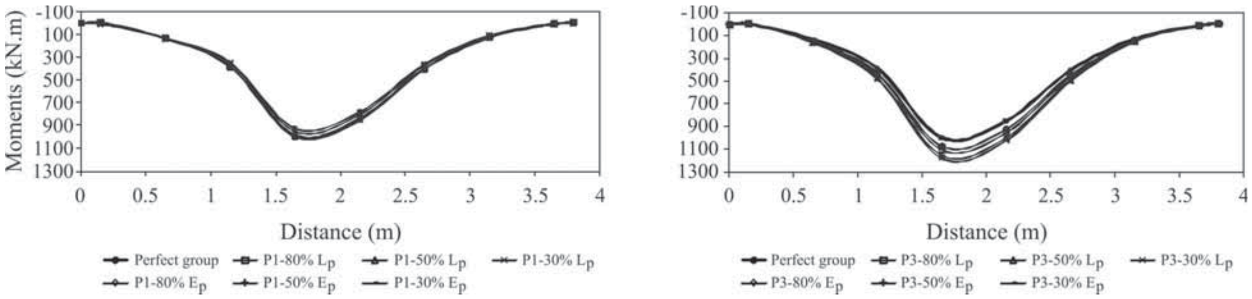

Figure 5 - Group behavior in terms of raft moment for imperfection on (a) pile 1 and (b) pile 3.

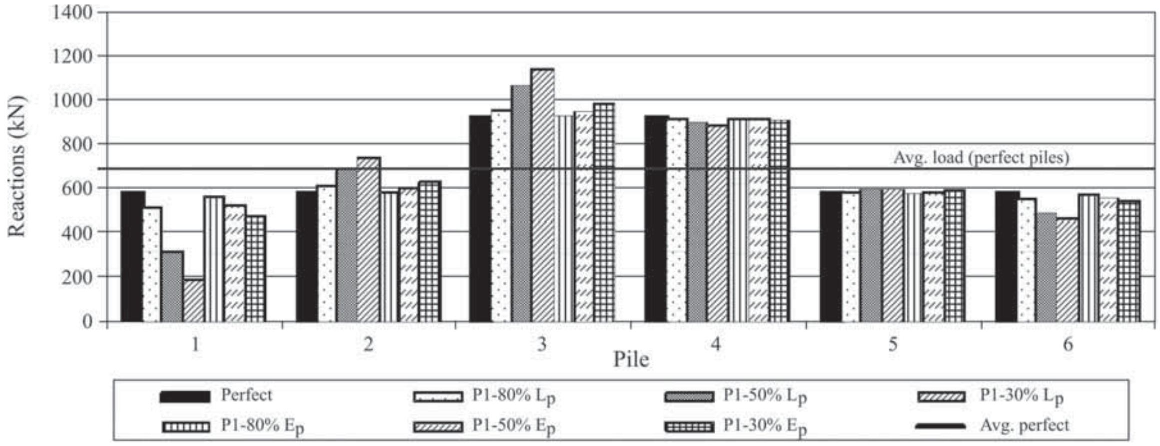

Figure 6 - Generated pile loads for imperfection on pile 1.

Table 2 - SF for imperfection on pile 1.

Damage level	Pile 1 (defective)	Pile 2	Pile 3	Pile 4	Pile 5	Pile 6	Overall SF
Perfect group	2.50	2.50	1.57	1.57	2.50	2.50	2.00
80% Lp	1.00	2.39	1.51	1.58	2.49	2.61	1.80
80% Ep	2.58	2.48	1.55	1.57	2.50	2.53	2.00
50% Lp	1.00	2.11	1.36	1.61	2.43	2.97	1.75
50% Ep	2.77	2.40	1.52	1.58	2.49	2.59	2.00
30% Lp	1.00	1.96	1.26	1.64	2.42	3.16	1.73
30% Ep	3.06	2.32	1.48	1.58	2.46	2.67	2.00
Fully damaged	-	1.78	1.16	1.64	2.37	3.47	1.69

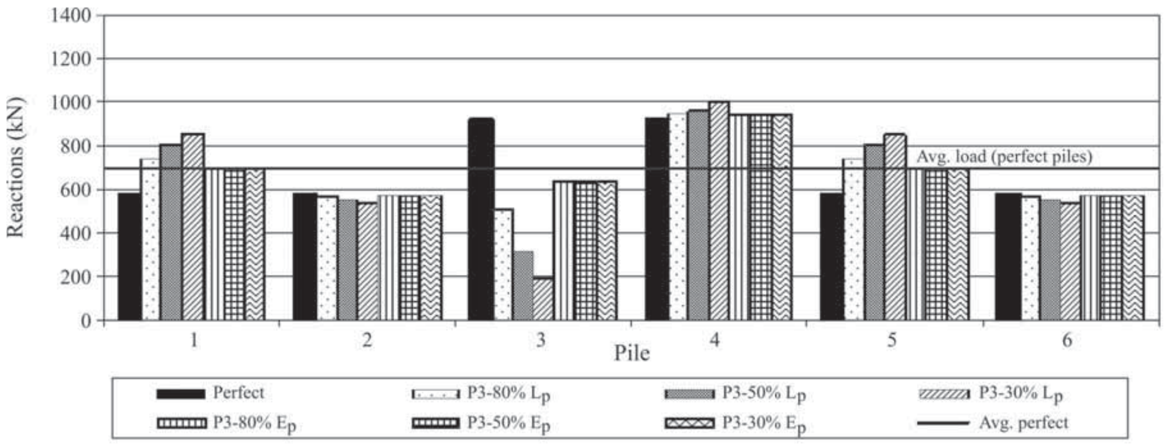

Figure 7 - Generated pile loads for imperfection on pile 3.

differently spreading it through the piles. Notice that piles 3 and 4 are those in the lower limit of SF, by their closer proximity to the column load. Such behavioral contrast between piles 3,4 and 1,2,5,6 will hold for all studied cases;

• For the case of imperfection caused by pile length variation it can be seen that the overall SF tends to decrease as the severity of the defect increases. At worst (fully damaged) conditions, the SF drops to values in the range of 1.7.

Table 3 - SF for imperfection on pile 3.

Damage level	Pile 1	Pile 2	Pile 3 (defective)	Pile 4	Pile 5	Pile 6	Overall SF
Perfect group	2.50	2.50	1.57	1.57	2.50	2.50	2.00
80% Lp	1.96	2.55	1.00	1.52	1.96	2.55	1.80
80% Ep	2.10	2.53	2.27	1.54	2.10	2.53	2.00
50% Lp	1.78	2.60	1.00	1.50	1.78	2.60	1.75
50% Ep	2.10	2.53	2.27	1.54	2.10	2.53	2.00
30% Lp	1.69	2.69	1.00	1.45	1.69	2.69	1.73
30% Ep	2.10	2.53	2.27	1.54	2.10	2.53	2.00
Fully damaged	1.57	2.68	-	1.39	1.57	2.68	1.69

Moreover, in terms of individual SF for each of the piles, independently on the defect position (pile 1 or 3), the individual SF caused by a variation on the pile length may, or may not, lead to lower individual SF than those caused by the stiffness variation. For instance, this can be noticed for pile 4 results in both tables;

• Although the overall SF is the same (at a particular imperfect condition) for both studied positions of the defective pile, individual factors for the piles vary considerably from one to another condition. Notice, for instance, that even defective, piles 1 and 3 continue to absorb load from the general distribution between raft and piles. But a defect (of any type) on pile 3 always leads this pile to lower individual SF than equivalent ones from pile 1. This is so given its aforementioned position in the raft, closer to the center of loading;

• Once a defect is imposed, for any of the imperfect group conditions, there is a transfer of load from the defective (dissimilar) pile to the similar ones of the group. The amount of load spread depends on the severity of the damage and leads to an increase of load (and reduction of SF) for some of the non-defective piles. For instance, for a defect on pile 1 the load is mainly spread to piles 2 and 3, while for a defect on pile 3 this same load is mainly spread to piles 1 and 5 and to a lesser degree to pile 4;

• It is also clear that the transference of load not only occurs from the defective pile to similar non-defective ones, but also from similar to similar piles. For instance, in any of the cases of defective pile 1, some load is spread from pile 6 to adjacent ones, leading to a decrease of load in this pile and correspondent increase of its individual SF. This happens due to aforementioned tilting of the raft towards the position of the defective pile.

Finally, Fig. 8 presents the load distribution for each of the studied cases of imperfect group, at both conditions of variable pile length and stiffness. The figure depicts the percentage value absorbed by the raft in all conditions, including the original perfect case.

From this one, it is clear that a pile defect caused by a variation on its length is more influential on the raft load than a proportional defect caused by a variation on the pile

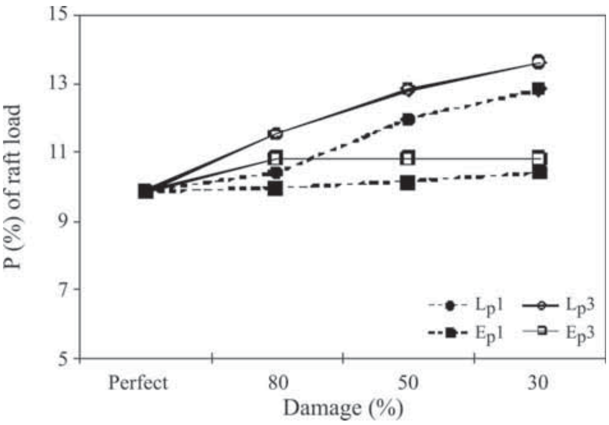

Figure 8 - Load distribution for imperfection on pile 1. (L_p1, E_p1) and pile 3 (L_p3, E_p3).

stiffness. As the severity of the defect increases, more load is gradually transferred from the piles to the raft.

Although the transference was small (maximum of 4% of working load), it definitively indicates a tendency of load transfer towards the raft in imperfect pile groups, transfer which may be of considerable amount in other rather more severe cases.

4.2. Post-reinforced conditions of the imperfect group

This section introduces the parametric analysis of the remediation of the imperfect group, by the insertion of a similar or dissimilar pile at a particular distance from the defective one.

In order to simplify the analysis, a few basic considerations were adopted, as:

• Just one defective pile was considered, in a fully defective condition, *i.e.* assuming that it simply did not exist at the reinforced case. This is a common assumption adopted in the remediation design of similar imperfect groups. For the analysis, pile 1 was chosen as the defective one, due to the more severe conditions imposed on the group, as noted before;

• Just one reinforcement pile was considered, located close to the defective one, in the region of the raft potentially subjected to more damage. It was assumed that the reinforcement was carried out by a previous geometry change of the raft, in the beginning of the process. Although it changes the geometrical and loading center, this is exactly what is done in some practical cases;

• The reinforcement pile was considered either with similar or dissimilar characteristics (length, diameter, stiffness) compared to the original undamaged piles of the group. This is also normally considered on remediation jobs of this type.

Figure 9 presents the general view of the four remediation cases considered herein, namely cases 1 to 4, respectively related to reinforcement piles R1 to R4. The equivalent distance to the defective pile, and cross section AA, are also depicted. The results will be shown in relation to this particular raft section.

4.2.1. Remediation with similar pile

Figures 10 and 11 respectively present the results in terms of normalized vertical settlement and moment generated along the raft length, for all cases of reinforcement. The perfect original (undamaged) condition and the fully damaged one (unreinforced case) are also depicted.

In this particular series of analyses the remediation was considered to have taken place solely with a similar reinforcement pile, *i.e.*, with the same length, diameter and stiffness as the original piles of the group.

From this series of results one may notice that:

• Once fully damaged, the pile group behaves very distinctively from the original condition in terms of normalized settlements. Nevertheless, in terms of generated moments, there are few numerical differences between the results at both conditions;

• All remediation cases improve the behavior of the reinforced raft in terms of normalized settlement, *i.e.*, decreasing the values along the studied section. By considering the average pattern all along original and extended raft, it appears that remediation cases 2 and 4 are more effective than cases 1 and 3, although with small differences.

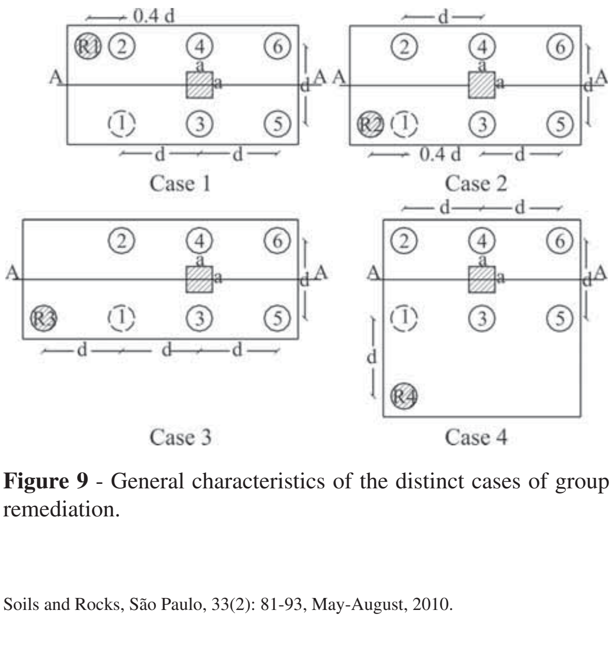

Figure 9 - General characteristics of the distinct cases of group remediation.

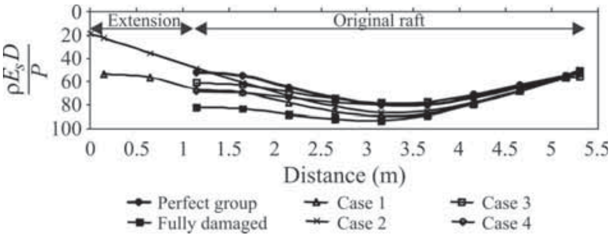

Figure 10 - Group behavior in terms of normalized vertical settlement for a similar reinforcement pile.

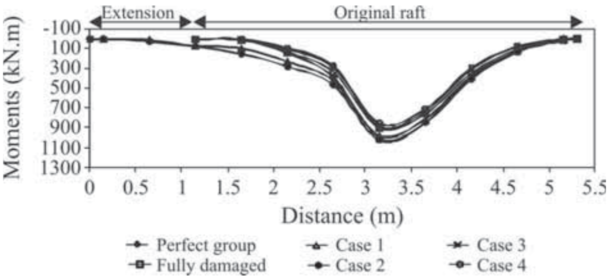

Figure 11 - Group behavior in terms of raft moments for a similar reinforcement pile.

• Contrary to what was initially expected, all remediation cases slightly aggravate the behavior in terms of moments, increasing them in relation to original (and fully damaged) conditions. The moment pattern is similar for all considered cases, and is largely influenced by the change on the raft's geometrical center and average flexibility once the reinforcement is imposed. From the studied conditions, and with minor differences, it appears that cases 3 and 4 are preferable to 1 and 2;

Figure 12 and Table 4 respectively present the reactions and the safety factors for all considered conditions, *i.e.*, perfect original, fully damaged and reinforced group.

Table 4, in particular, presents individual safety factors for each of the original and reinforcement piles, as well as the overall SF of the group for all considered cases. The overall SF considered the enlarged condition of the raft plus the contribution of the reinforcement pile, at each remediation case.

From these results, one may notice that:

• The overall SF has increased to acceptable values (> 2) in all reinforcement cases, reaching original pre-defect conditions. However, as for the imperfect group, there is a natural variation of individual factors for each pile. This variation holds for all cases, and, as before, piles 3 and 4 continue to be those in the lower limit of SF;

• Once reinforced, the group returns to a more uniform condition when compared to the fully damaged case. In the latter case, given the absence of one of the piles and

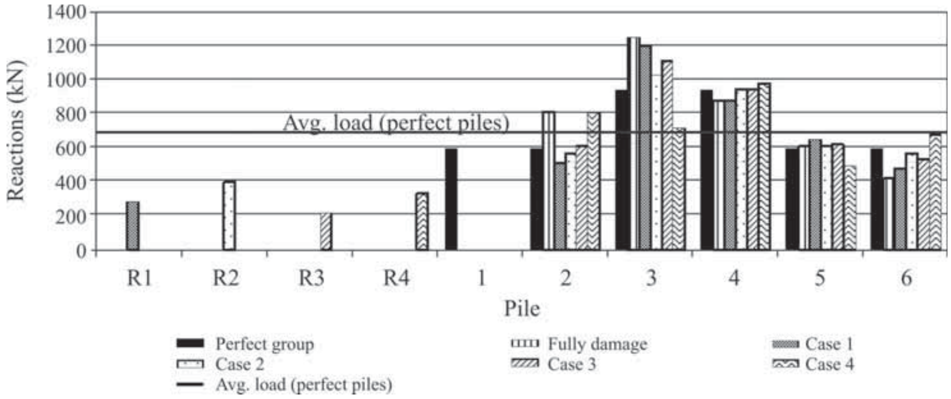

Figure 12 - Generated pile loads for all reinforced cases.

Table 4 - SF for reinforced cases of similar pile.

Pile	Perfect group	Fully damaged	Reinforcement type			
			Case 1	Case 2	Case 3	Case 4
R1	-	-	5.23	-		-
R2	-	-	-	3.67	-	-
R3	-	-		-	6.97	-
R4	-	-	-	-	-	4.48
1	2.5	-	-	-	-	-
2	2.5	1.78	2.84	2.55	2.38	1.79
3	1.57	1.16	1.21	1.41	1.29	2.03
4	1.57	1.64	1.64	1.53	1.53	1.47
5	2.5	2.37	2.24	2.40	2.33	2.94
6	2.5	3.47	3.07	2.55	2.71	2.14
Overall SF	2.00	1.69	2.00	2.00	2.02	2.03

the resultant spread of load, there is a large variation on the individual SF (1.78 to 3.47). For instance, taking on account the general pattern of load distribution and individual SF, it is clearly seen that, once the group is reinforced, piles 2 and 3 decrease their load, while piles 4 and 6 increase it. Also, depending on the reinforcement type, pile 5 may increase or decrease its internal load. This behavior is undoubtedly related to each pile position within the group, to their individual proximity to the defective one, plus aforementioned effects of the raft's geometrical center and average flexibility;

• Although all reinforcement cases proved to remediate the group to acceptable levels (of presented variables), the reinforcement piles failed to behave efficiently on working conditions. That means, they lacked to absorb most (or all) of the load spread caused by pile's 1 defect, hence they behaved conservatively in all cases. A better design, not implemented herein, would enhance the performance of piles 3 and 4 at post-reinforced conditions, leading them to a SF closer to original (undamaged) values. Note for instance the low individual SF of pile 3 at reinforcement cases 1 to 3, and of pile 4 at cases 2 to 4;

• It is also clear that for some piles, when comparing to original perfect conditions, there was an aggravation of the behavior by the imposed remediation, *i.e.*, they had a lower individual SF in relation to initial values. Perhaps, in other more severe situations some of the piles would be fully mobilized, even at the reinforced raft stage;

• Indeed, to lessen the conservative performance, the reinforcement piles could have been designed with distinct characteristics from the original ones, perhaps with shorter lengths or diameters. This aspect will be explored in the next topic.

Finally, Fig. 13 presents the load distribution for each of the studied reinforced cases, and their comparison to original and fully damaged values. From this one it is noticed that, by reinforcing the raft, it tends to transfer load back to the piles (original and reinforcement ones).

Depending on the reinforcement case, more load is gradually transferred from raft to piles, but, as previously

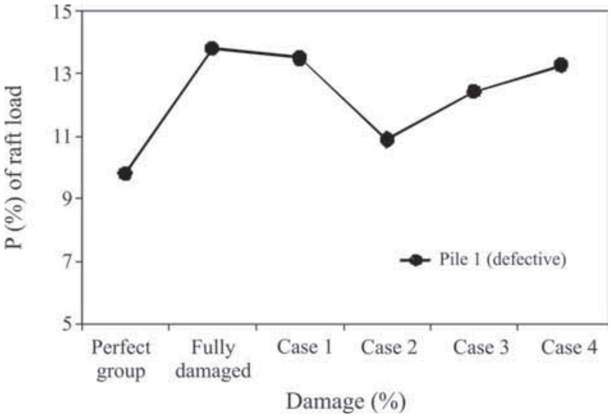

Figure 13 - Load distribution for reinforced cases.

commented, the effectiveness of the reinforcement systems was not ideal. That means, they failed to return the raft load to original perfect conditions, although some improvement is made in regard to the fully damaged case.

4.2.2. Remediation with dissimilar pile

The remediation with a dissimilar pile adopted solely the reinforcement case 4 as the parameter for comparison, due to its better performance on previous analyses. The dissimilar pile was simulated with respectively 50% of the original length, diameter, and stiffness, of the original piles.

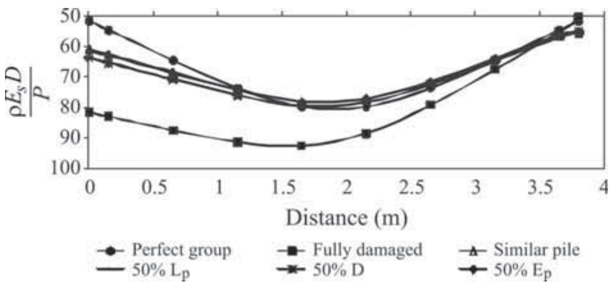

Figure 14 - Group behavior in terms of normalized vertical settlement for dissimilar reinforcement pile.

A comparison with former results (similar pile reinforcement) is also provided.

Hence, Fig. 14 and Table 5 respectively present the results in terms of normalized vertical settlement and safety factors for all considered cases.

From them, it can be noticed that:

• In terms of normalized settlements (and moments, not shown), there isn't much difference in reinforcing the raft with similar or dissimilar piles. All the results are good enough to be accepted in practical terms. Nevertheless, the reinforcement with dissimilar piles may prove to be more economical;

• In terms of individual SF it is clear that the dissimilar piles with 50% length or diameter behave less conservatively at working conditions than the similar pile. Nevertheless the overall SF values of the group for these cases tended to be lower than the minimum value advocated by normal standards;

• On the other hand, in terms of individual and overall SF for the reinforcement with a dissimilar pile with 50% of the original stiffness, it can be noticed results as good as those of the reinforcement with a similar pile. Hence, it appears from these (limited) tested cases that the usage of dissimilar piles with reduced stiffness seems to be preferable in a reinforcement event. However, this conclusion needs further validation, also taking into account the economical aspects of the problem.

5. Conclusions

This paper has explored and extended the design philosophy of "piled raft" to forecast the numerical behavior of imperfect pile group foundations at pre and post-remediated conditions.

Although the results are restricted to the conditions of the analyses, they allow preliminary generalizations of the overall behavior. Moreover, they do highlight the fact that the phenomena involved with such processes are rather complex, but feasible to be simulated in a simplified manner. More elaborate analyses could have been employed to

Table 5 - SF for reinforced cases of dissimilar pile.

Pile	Perfect group	Fully damaged	Reinforcement type			
			Similar pile	50% Lp	50% D	50% Ep
R4	-	-	4.48	1.66	2.10	5.05
1	2.5	-	-	-	-	-
2	2.5	1.78	1.79	1.77	1.76	1.78
3	1.57	1.16	2.03	1.95	1.89	1.96
4	1.57	1.64	1.47	1.49	1.49	1.48
5	2.5	2.38	2.94	2.95	2.94	2.93
6	2.5	3.47	2.14	2.21	2.24	2.19
Overall SF	2.00	1.69	2.03	1.79	1.82	2.07

cope with most (or all) of the aspects involved in the simulations, but at the expense of a much more complex numerical tool and longer time span.

The analyses have also allowed a reasonable insight into some of the most relevant variables that affect the behavior of the group foundation once it is damaged, *i.e.*, once it is loaded with the presence of a defective pile(s). They have as well provided a better understanding of the mechanisms which are involved by the remediation of this same foundation, via introduction of either similar or dissimilar (reinforcement) piles compared to those of the original group, at early loading stages.

From the general aspects observed with the analyses, some general conclusions can be drawn:

1. The behavior of the group foundation once an imperfection is imposed at working load will be undoubtedly degraded in relation to that which would occur at normal conditions. That means, settlements and moments on the raft will increase, and load transference between defective to normal, and normal to normal pile, will certainly take place. The level of load spread and raft tilting will depend on the severity of the defect, *i.e.*, the location and number of defective pile(s), the degree of defect and overall pile-raft characteristics (geometry and flexibility);

2. A pile defect caused by a variation on its length (reduced length in regard to normal similar piles) is more influential on the foundation variables than a proportional defect caused by a variation on the pile stiffness;

3. The foundation settlement is more influenced by the pile defect than the moment generated at raft, at working conditions;

4. Imperfect pile groups will also have degradation on the individual pile, and overall group, (geotechnical) safety factor. The overall SF will decrease as the severity of the defect increases, and individual pile SF may decrease (load gain) or even increase (load loss) due to load redistribution that normally occurs during this stage;

5. Once an imperfection is imposed there is a normal variation (or transference) of load from the piles to the raft. During this process, the defective pile transfers some of its original load to the raft as well as to adjacent normal piles, depending on the geometry of the raft, pile position and severity of the defect. Once remediated, the group tends to transfer less load from the piles to the raft, though the transfer continues to exist;

6. Even when imperfect, the defective pile continues to absorb some load, but to a lesser degree than the original value (of the perfect group condition). This particular feature can be wisely used in design;

7. The remediation of the foundation via insertion of a unique reinforcement pile close to the defective one improves the group behavior in terms of settlement and overall group SF, if such procedure is carried out at early stages of loading;

8. On the contrary, it can also degrade the foundation behavior in terms of raft moments, from the fact that it will inevitably change the raft's geometrical center and overall flexibility;

9. The reinforcement also provides a redistribution of load within group components, *i.e.*, the load spread from the defective pile will be partially absorbed by the reinforcement one, and some of the normal piles of the group may lose load (increasing their individual SF), while others, on the contrary, may gain load (decreasing their individual SF). This behavior is related to each pile position within group, type of reinforcement (*i.e.*, similar or dissimilar pile), plus aforementioned aspects of defect severity and raft geometry;

10. At extreme cases of imperfection, not carried out herein, it is feasible that some of the normal piles of the reinforced group can be fully mobilized, *i.e.*, with individual SF very close or equal to unity;

11. An optimization of the remediation is required to enhance the performance of the group at post-reinforced conditions, *i.e.*, to have most of the load of the defective pile transferred to the reinforcement one, with minimum levels of interference on adjacent normal piles;

12. Such optimization will undoubtedly take place by an initial study of the better location of the reinforcement pile on the original or extended raft, and by a suitable (in technical and economical terms) choice for the type of reinforcement, which most probably will be the use of dissimilar piles in relation to the normal ones of the group;

13. The effectiveness of the reinforcement, considered solely on technical terms (*i.e.*, safety factors) is better when adopting dissimilar piles with reduced stiffness, than when reinforcing the raft with a dissimilar pile of reduced length or diameter. This conclusion, however, is still subjected to further validation.

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